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Ephemeris Estimation of a Well-Defined Platform Using Satellite Laser Ranging from a Reduced Number of Ground Sites

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13. ABSTRACT (Maximum 200 words) This study presents the results of an analysis comparing ephemerides obtained using Satellite Laser Ranging (SLR) derived from a reduced number of ground sites. The study provides insight into the extent to which ephemeris can be determined for an extremely well-specified satellite. The study was conducted to determine the viability of using a single SLR site to provide an independent method of verifying onboard Global Positioning System navigational performance. Computational simulations included varying the number and distribution of sites as well as empirical modeling of nonconservative forces to determine the limitations of this SLR-based reduction strategy.				
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EPHEMERIS ESTIMATION OF A WELL-DEFINED PLATFORM USING SATELLITE LASER RANGING FROM A REDUCED NUMBER OF GROUND SITES

1. INTRODUCTION

The goal of this study was to determine the efficacy of Satellite Laser Ranging (SLR) as an independent means of validating Global Positioning System (GPS) navigational performance using a subset of the international SLR network. Specifically, satellite ephemerides of TOPEX/POSEIDON using a reduced number of SLR ground sites were determined under varying conditions by using different analytical tools. Computational experiments were conducted using GEODYN [1], DELTA, and orbit determination and analysis programs generated by the Naval Research Laboratory (NRL).

2. BACKGROUND

Satellite Laser Ranging is essentially radar in the optical regime. In the context of this study and in the National Aeronautics and Space Administration (NASA) SLR community, it refers to direct detection optical radar. The round-trip time delay between an optical transmit/receive site and a satellite is (1) time-tagged; (2) corrected for atmospheric and other effects; and (3) reduced in an orbit determination model, which generates orbital ephemeris, absolute position, or both, depending on the analysis tool used. Figures 1 and 2 illustrate the technique.

Satellite ephemeris is normally determined from the international SLR network. This network comprises 44 stations including the NASA, NRL/Starfire Optical Range (SOR), European, Australian, and Asian networks. The weighted root-mean-square (RMS) orbital fit from a multi-day LAGEOS arc is typically on the order of 2 cm, where LAGEOS is a geodetic spacecraft used for calibration and geoscience [2]. Figure 3 illustrates the global distribution of the network.

The study focused exclusively on the TOPEX/POSEIDON satellite. TOPEX was chosen because of its orbital parameters, data density, and on-board GPS receiver. The TOPEX/POSEIDON experiment is tasked with measuring the displacement of the ocean surface to 3 cm, knowing satellite position to 15 cm RMS. TOPEX is of great interest to the international SLR community for navigational reasons as well as for geoscience [3].

GPS is perceived to be the method of the future for spacecraft (s/c) navigation. One of the major aspects of relevance to the Navy is that the TOPEX mission has shown that SLR can independently verify differential GPS performance. The two methods agree in their orbit estimates to within 15 cm. Figure 4 shows how GPS performance and SLR independently verify spacecraft position.

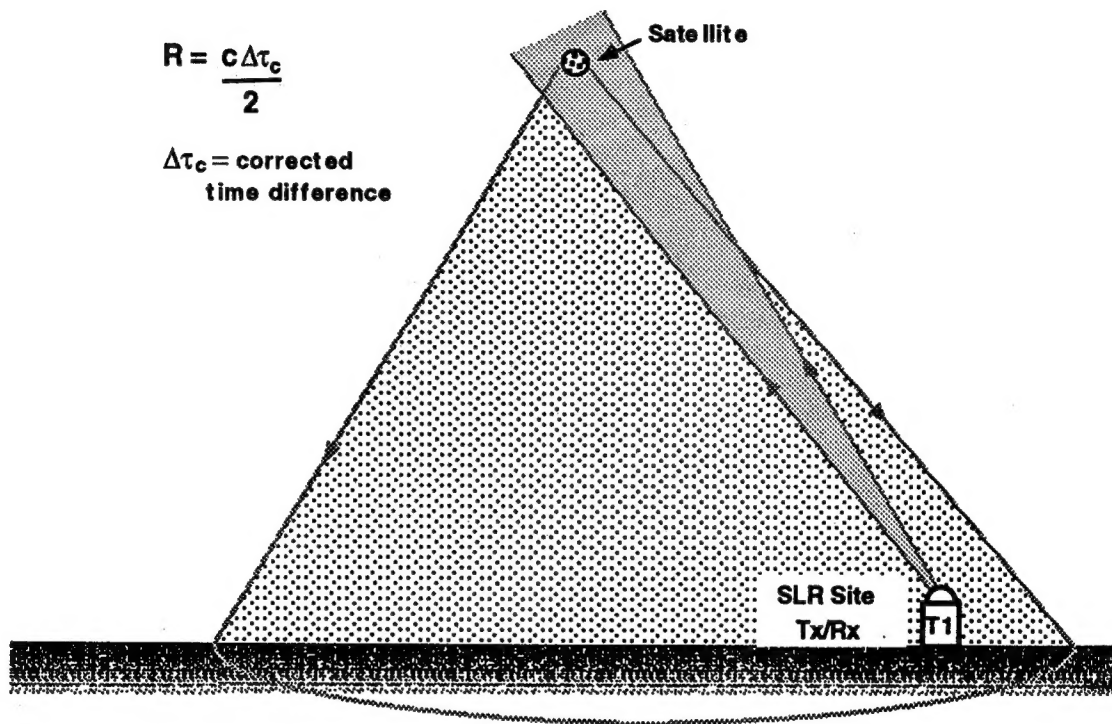


Fig. 1 — In direct detection satellite laser ranging, the time-tagged round-trip delay is corrected for atmospheric and other effects to obtain the radial range from a ground site to the satellite

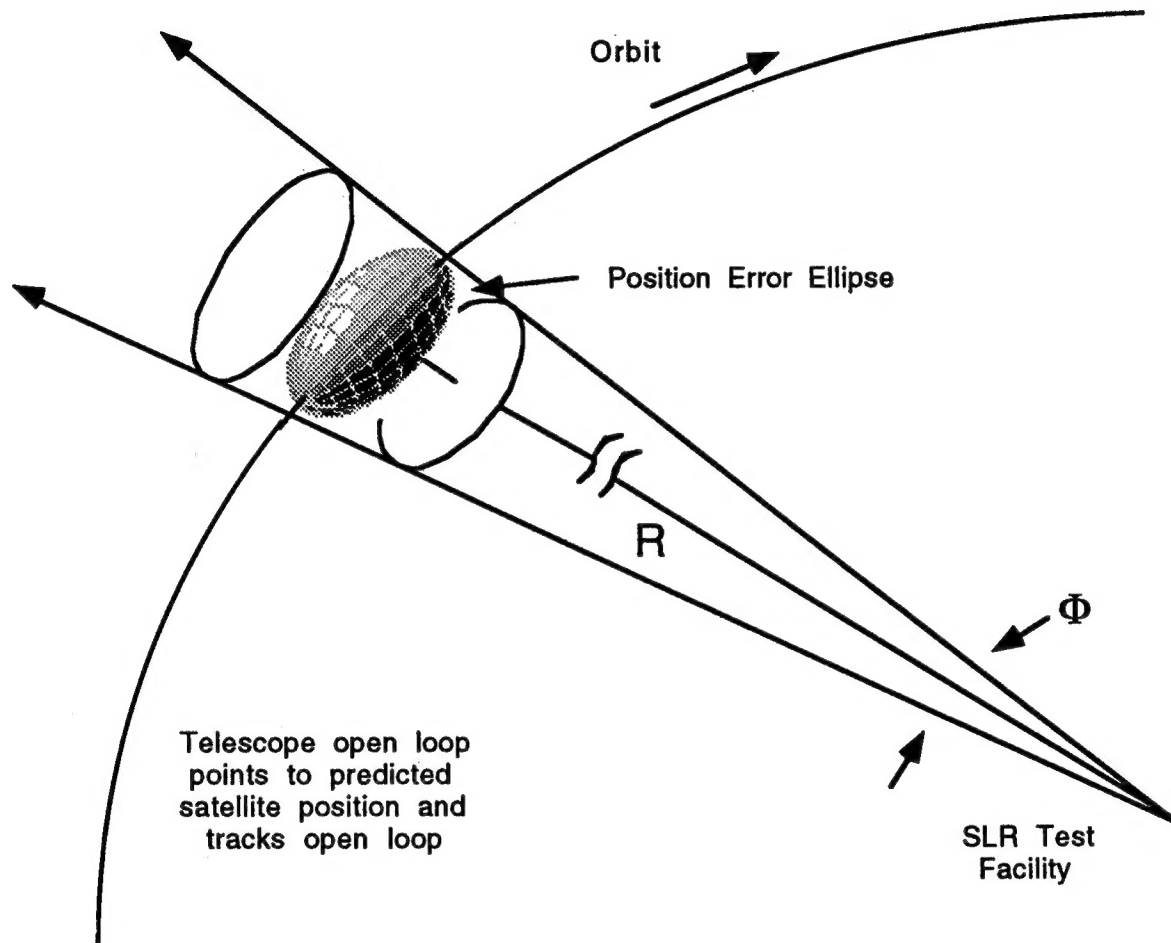


Fig. 2 — The radial range obtained as shown in Fig. 1 is entered into an orbit determination model to determine the error ellipsoid of the satellite over the orbit or at a given time. The position is typically expressed in terms of in-track, cross-track, and radial components. The total position is computed by taking the RMS of these components.

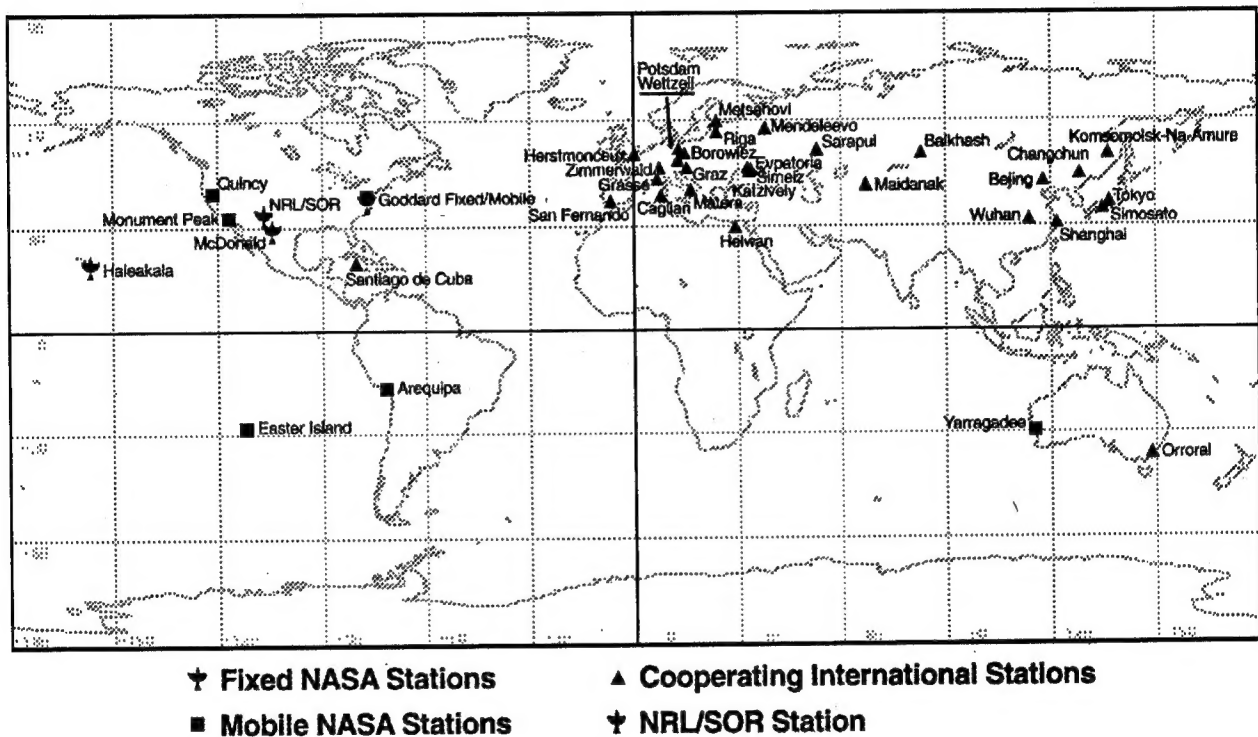


Fig. 3 — The international SLR network comprises more than 40 stations. This network includes the NRL/United States Air Force (USAF) Phillips Laboratory (PL) node located at the Starfire Optical Range (SOR) in Albuquerque, NM.

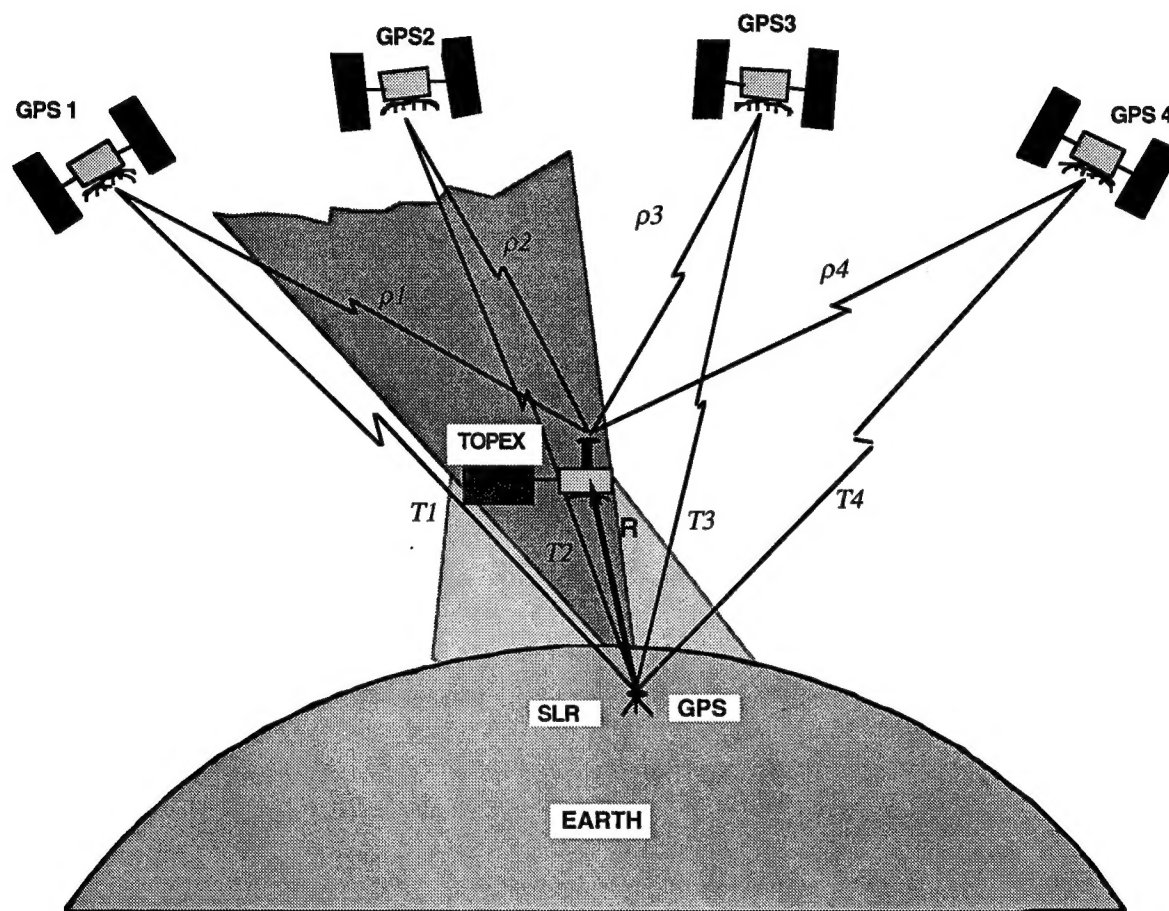


Fig. 4 — Independent verification of on-board GPS performance using Satellite Laser Ranging. Pseudo ranges are transmitted from the NAVSTAR constellation to the GPS receivers on the spacecraft and at the ground site. The pseudo ranges are corrected and differenced to obtain range. SLR obtains radial range measurements through direct detection. Ranges are reduced in orbit determination models and compared.

In this study, computational experiments were conducted using historical TOPEX SLR data to simulate the performance of a single dedicated SLR site. NASA scheduling guarantees that coverage lapses due to shift downtime are minimized for TOPEX. Hence, the observations obtained for TOPEX are representative of the data density and distribution that a dedicated single-site could achieve. If TOPEX had lower tracking priority, the fidelity of single-site results could not be assessed as readily. As would be the case with a dedicated site, the data dropouts from the more extensive coverage were caused by weather outages and station downtime caused by shift constraints or technical problems. In all results reported in this study, adverse weather considerations have been built into the data implicitly. The shift issue, however, is addressed in Section 4 of this report.

3. METHODOLOGY

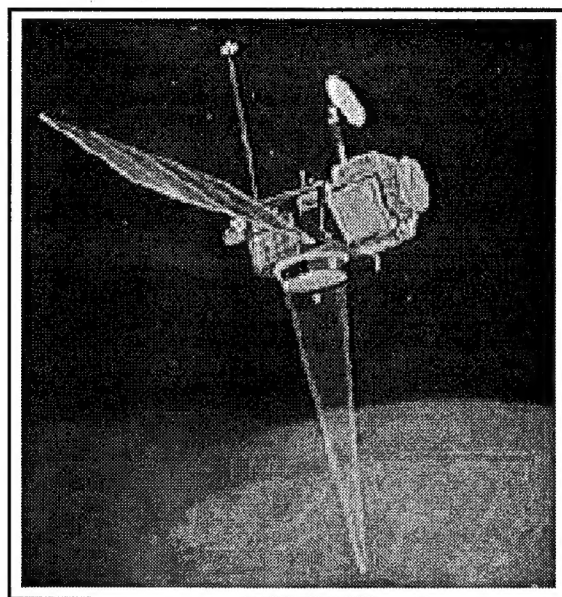
Figure 5 depicts the TOPEX satellite and diagrams its payloads. Table 1 gives the satellite's orbital parameters. The orbital parameters produced a repeat ground track of 127 revolutions in 9.92 days.

Table 1 — Orbital Parameters for TOPEX

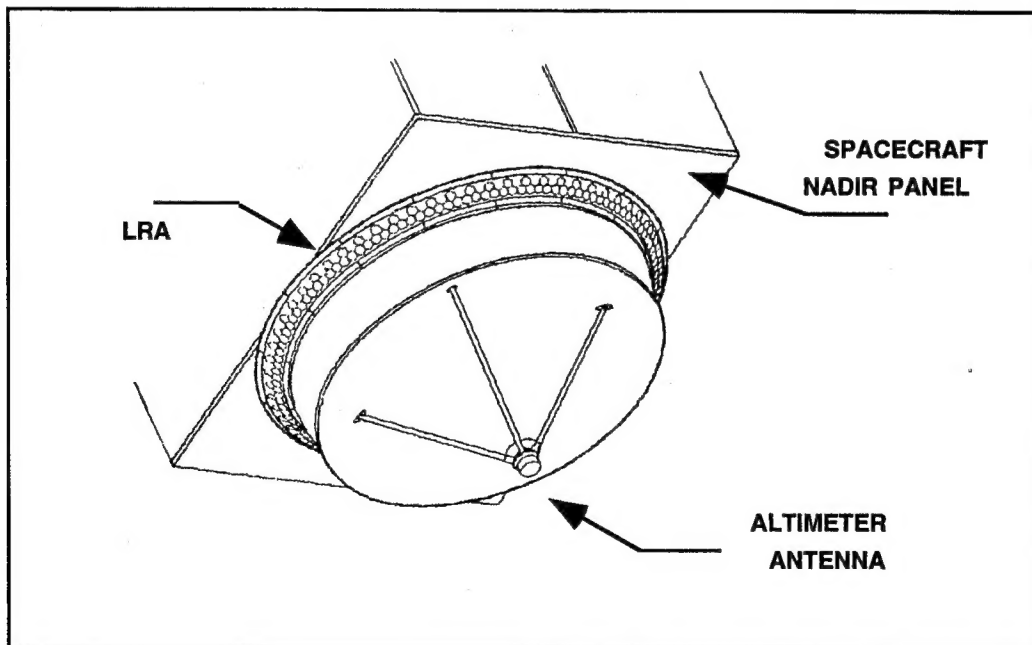
Orbit	Circular
Altitude	1,337 km
Inclination	66°
Period	112.2 min

Although a number of analytical tools were used in the study, GEODYN provided the primary means of analysis conducted by NRL [4]. GEODYN operation started with a nominal estimate of the initial position and velocity of TOPEX, referred to as initial conditions (ICs). When combined with the spacecraft specifications and the orbit models contained in GEODYN, the ICs were sufficient to propagate the trajectory of TOPEX to a specified time in the future. If GEODYN operated in a purely predictive mode, excluding SLR measurements to improve ephemeris predictions, the ephemeris accuracy would be significantly degraded after a few days. GEODYN then produced the ephemeris of the satellite during the period of interest. It then compared the calculated range of TOPEX with the observed range for each of the observations from the individual SLR sites over the specified time interval. GEODYN then adjusted its estimate of the initial conditions and the resulting orbit to minimize the sum of these residual errors by using a least-squares fitting process. GEODYN used state-of-the-art force models for its solution. The most significant models were as follows: JGM2 for the geopotential, GEM-T3 for ocean tides, DTM for atmospheric drag, and a box/wing "macro-model" for radiative effects. TOPEX-specific platform parameters were provided by NASA/Goddard Space Flight Center (GSFC—referred to as Goddard in this report).

The outputs from GEODYN used in this study included ephemeris, RMS range residuals, and normal points. Range residuals are defined as the one sigma scatter from the mean generated from observations. Normal points refer to the statistical reduction of raw laser ranging observations. Normal point bins vary depending on the satellite altitude. TOPEX normal point bins are 15 seconds. The GEODYN ephemeris files were used as inputs to the DELTA program. DELTA then calculated the average RMS differences in radial, cross-track, along-track, and total position between the GEODYN ephemeris and a baseline ephemeris over a specific period of time.



(a)



(b)

Fig. 5 — (a) Illustration of the TOPEX satellite. (b) The Laser Retroreflector Array (LRA) consists of a double ring of retroreflectors.

All results are expressed as a difference with respect to the "truth" as defined by the Precision Orbit Ephemeris (POE). The POE is generated for TOPEX in 10-day cycles and is derived from SLR and Doppler Orbitography and Radiopositioning Integrated from Space (DORIS) data. The stated RMS position accuracy of the POE is 3 cm to 4 cm radial, 8 cm to 10 cm cross-track, and 10 cm to 15 cm along-track [5]. The absolute position error would have been determined by taking the root sum square (RSS) of the position "differences" and the POE ephemeris error for the specific radial, cross-track, or along-track component. However, the correlation coefficient was unknown, so the computation could not be made accurately.

NRL-generated programs developed for this study were used to determine orbit position vs time and the minimum SLR station configuration requirements for achieving submeter orbital ephemeris. Specifically, parameters such as number of passes, zenith elevation, revisit times, and site distribution were accessible through the NRL processing tools.

A subset of the international SLR network was examined for suitability in single-site orbit determination by using GEODYN. Using laser observations from TOPEX, the ephemeris was generated and then compared with the POE to establish orbit-averaged position differences. This methodology was then repeated for the multiple-site analysis. Building on the single-site orbit determination result, the observations from additional sites were added incrementally to examine the improvement in the ephemeris solution. This study examined three TOPEX 10-day cycles (39, 40, and 41) for the period of Oct. 4, 1993 to Nov. 4, 1993.

TOPEX precision orbit estimates are normally optimized by NASA/Goddard with GEODYN using empirically adjusted anomalistic accelerations (AA) with nominal atmospheric drag and solar radiation pressure (D/R) parameters. The AA compensated for the unexplained but observable perturbations acting on the satellite in its orbit. The nominal D/R values were calibrated by NASA/Goddard based on prior observations from the global SLR network. Due to the abundance of data, the AA could be determined effectively from the complete network. However, the NRL analysis indicated that solving for AA from a single site was not possible. In all cases, the solution was "ill-behaved" due to the paucity of observations and gaps in coverage.

A series of cases using GEODYN was run for comparison. These cases included fixed AA and fixed D/R; no AA and fixed D/R; and no AA and varying D/R, for both single and multiple sites. These cases are summarized in Section 5. Additional computational simulations were conducted to determine the impact of data density and distribution. Optimization of solution intervals was also investigated. GEODYN's ability to correct for biases applied to the initial conditions was assessed. The effectiveness of performing sequential GEODYN runs without a priori knowledge from existing POE ephemerides was examined as well.

Finally, operational implications for shift selection in both the single- and dual-site cases were explored. As a result of this latter set of computational experiments, an assessment was made of the importance of running two shifts at the SLR ground sites for both the single- and dual-site cases. In these cases, the ascending and descending passes, which correspond to the day and night shifts, were systematically removed to evaluate the ability of one shift at a single site to update an orbit. Results were compared to those using a pair of cooperating single-shift sites that obtained data from complementary passes.

4. RESULTS

4.1 Single-Site Analysis

In the first part of the NRL analysis, the extent to which a single site could estimate the TOPEX orbit was determined for different single sites. For example, the satellite ephemeris difference with respect to the POE was determined when Monument Peak was chosen as the single site. Its orbital estimate was compared to that determined when Yarragadee was selected as the single site. Nine globally distributed SLR sites were individually compared in this manner using GEODYN and DELTA. Such a study enabled separation of variables such as data density and orbital sampling as well as site quality in the determination of satellite ephemeris.

The ephemeris from each single site was compared with the POE to determine the RMS position differences. Total position differences were graphed for each of the nine sites. In the first set of results, D/R parameters were fixed. In the second set, the D/R parameters were allowed to vary, which permitted GEODYN to more accurately model the satellite's trajectory. For both cases, no AA adjustments were made to the orbit for the reasons described in the previous section.

Figure 6 shows RMS total position differences vs number of observations for each of the nine sites. Results for Cycle 39 demonstrated that approximately 500 normal point observations were necessary for submeter ephemeris determination. Results show a substantial improvement in the solution by recovering the D/R parameters. For example, the position difference for Yarragadee (7090) was 126 cm RMS with no D/R adjustment and 38 cm RMS with recovered D/R terms. When recovering the D/R parameters, two consecutive D/R terms were solved for during the 10-day cycle with their boundary set after half the total number of passes.

Figure 7 shows the total position difference with respect to the POE as a function of number of passes. This plot indicates that approximately 15 passes are necessary for submeter accuracy for this data cycle. The number of passes was a better variable for predicting position accuracy than was the number of observations, as indicated from Figs. 6 and 7. From the perspective of orbital sampling, distribution of data is more important than data density and this was borne out by each data cycle examined.

4.2 Consecutive TOPEX Cycles

The next part of the study concerned self-generated initial conditions. ICs refer to the satellite's position and velocity at a specific epoch. These values were then used with the SLR data to propagate an orbit using the GEODYN orbit determination model. It is of interest to assess the viability of producing new ICs using SLR data obtained from a single site directly and propagating those ICs through contiguous cycles. If this is successful, meter-level state vectors for orbital prediction may be achievable.

Three TOPEX cycles were selected for this set of computational experiments: 39, 40, and 41. The site selected as the single SLR node was Monument Peak. The repeat ground track for TOPEX produced approximately 36 possible tracking opportunities over this site during any 10-day cycle. This number varied slightly since passes near the boundaries of each 10-day cycle were routinely used in the orbit update for both cycles. The boundary area between 10-day cycles overlaps approximately 12 hours. If data were taken from a pass in the boundary region, those data were used in both cycles.

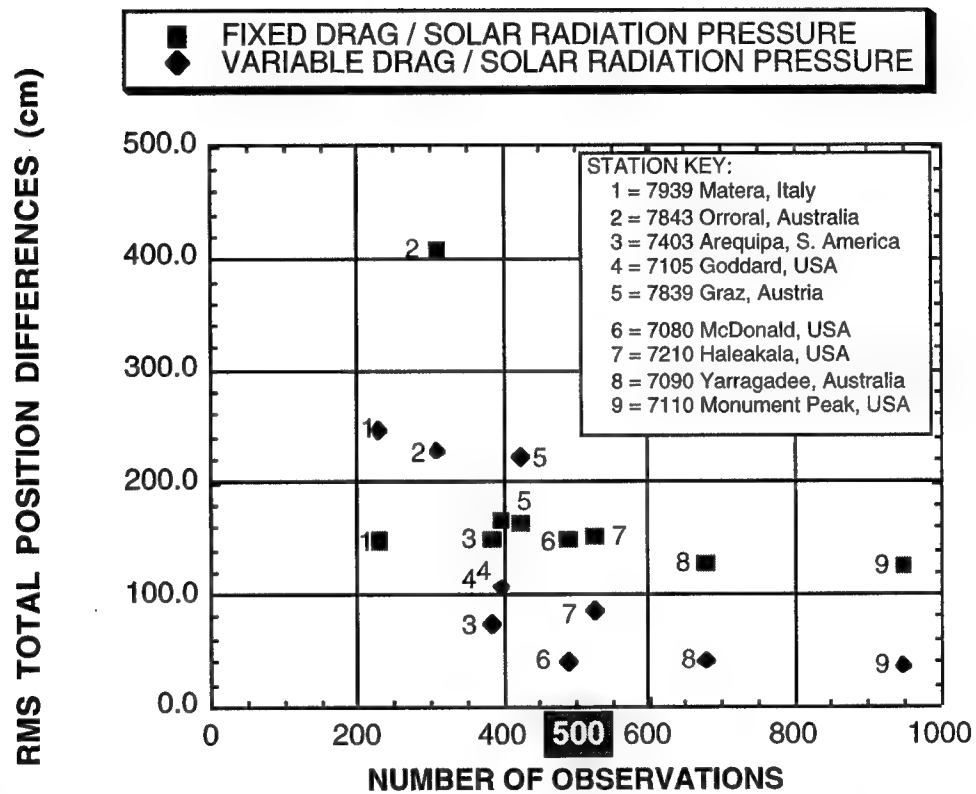


Fig. 6 — Results from nine independent SLR sites show approximately 500 normal point observations are needed for submeter accuracy over the 10-day cycle examined. Each estimate is the position differenced with respect to the POE.

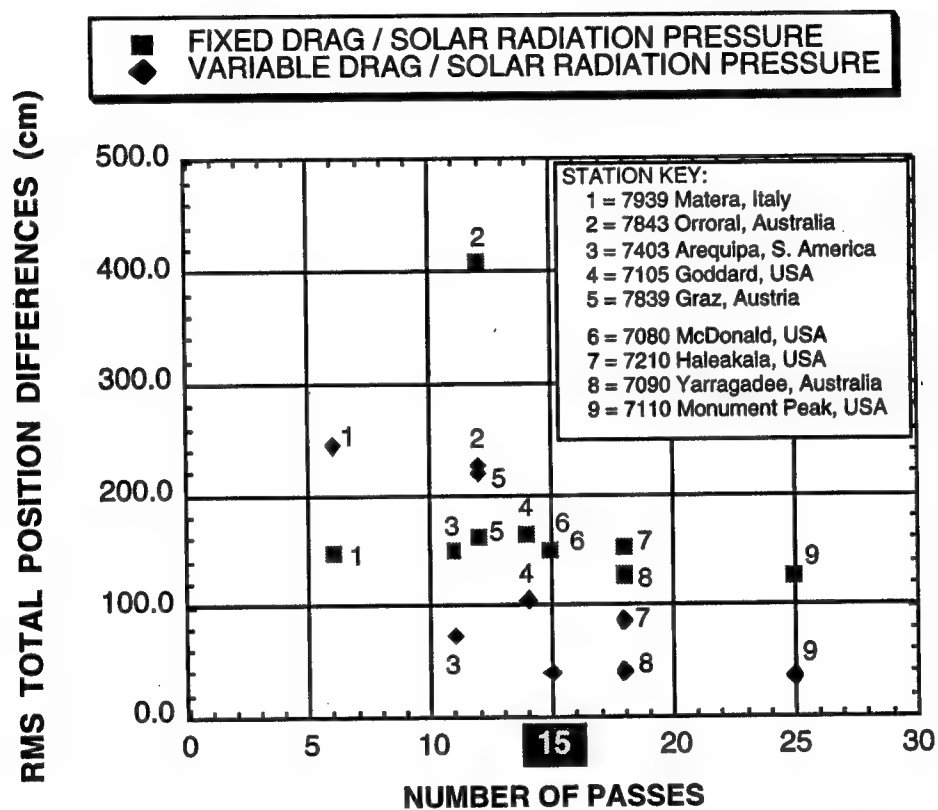


Fig. 7 — Results from nine SLR sites show a minimum of 15 passes are needed for submeter accuracy over the 10-day cycle examined

During Cycle 39, Monument Peak tracked TOPEX in 27 out of 36 possible passes. Six of the missed passes were consecutive from October 10 at 2200 through October 12 at 0100. Two of the remaining missed passes occurred during consecutive passes on October 8. The final missed pass was on the 9th. The Appendix provides a summary of SLR observations for the TOPEX cycles studied. Tables A1 through A3 provide a detailed description of each cycle. This period represented robust data acquisition consisting of two long periods of continuous coverage. The largest gap in data collection lasted about 2 days.

Conversely, in Cycle 40, TOPEX was tracked on only 13 of 37 possible passes. For 4 days in this cycle, no passes were taken by Monument Peak. In fact, during the first 4 days of this cycle, only three passes were taken at the site. Although some of this outage was caused by technical problems at the site, the majority of the data outage was caused by weather patterns moving over the site.

On the last 10-day cycle in October, Cycle 41, TOPEX was tracked on 23 of 38 possible passes. There was only one completely missed day during this interval, with many individual passes missed. This indicated transient weather problems during the cycle.

Initial conditions for succeeding cycles were determined from the previous cycles. As with previous analysis, no AA and two D/R parameters were recovered per cycle in postprocessing. Figure 8 shows the RSS total position difference over the 30-day period for the global SLR network and for Monument Peak (7110). The plot demonstrates that a single site is capable of producing submeter ephemerides for three consecutive 10-day cycles using the TOPEX satellite. The diamond markers on the plot show when measurements were made during a pass. There was a strong dependence on the number of passes and their distribution. For example, Cycle 41 had fewer observations and one less pass than Cycle 39, but it produced a better solution (33 cm vs 42 cm RMS). The improvement is due to a more uniform distribution of data. Peaks in the plot occur where data was sparse and at the beginning and end of each 10-day cycle as often seen from the "bow-tie" effect [6]. These effects are inherent characteristics of this least-squares estimator.

Cycle 40 had only 13 passes and poor pass distribution. Two passes of data were added to the beginning of the cycle, which still produced a substantial increase in RSS position difference from 42 cm to 68 cm. A close comparison of the two cases demonstrated the strong influence of Monument Peak on the all-site ephemeris solution. As seen in Fig. 8, the difference plots for both cases display some similar features. This was due to the large number of observations contributed to the ephemeris solution by Monument Peak as compared with the other stations in the SLR network for that specific period of time. The tendency of the global estimate to follow a strongly weighted single station can also be observed in the orbital components. Figure 9 is a plot of the radial difference component for the three cycles studied. The strong dependence on number of passes and their distribution is evident from the figure, where the radial RMS differences are 10 cm, 16.3 cm, and 10 cm, respectively, for cycles 39, 40, and 41.

A series of computational experiments were conducted to reduce the range residuals for Cycle 40 and test the sensitivity of GEODYN to input variables. Figure 10 illustrates the sequence of results obtained. At the beginning of this cycle, the RSS total position difference with respect to the POE was 7.5 m. Initial conditions predicted from Cycle 39 were used. D/R and ICs were varied by GEODYN during the solution interval. Figure 10(a) shows the original solution with an instantaneous difference of 7.5 m at the beginning of the cycle obtained with 13 passes of data. This cycle, described previously, had poor pass distribution and large data gaps. Two consecutive D/R terms were being solved for with their boundary set halfway in time through the cycle.

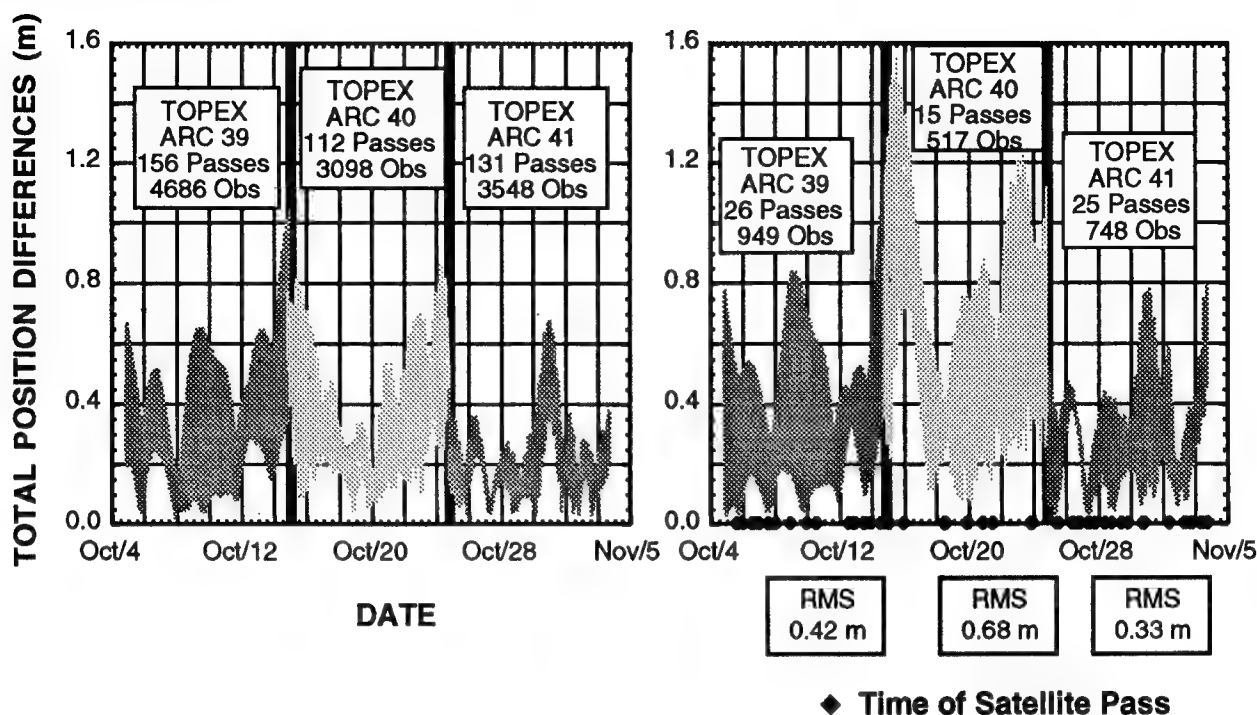


Fig. 8 — Total position difference with respect to POE for three consecutive 10-day TOPEX cycles for (a) all SLR sites and (b) Monument Peak

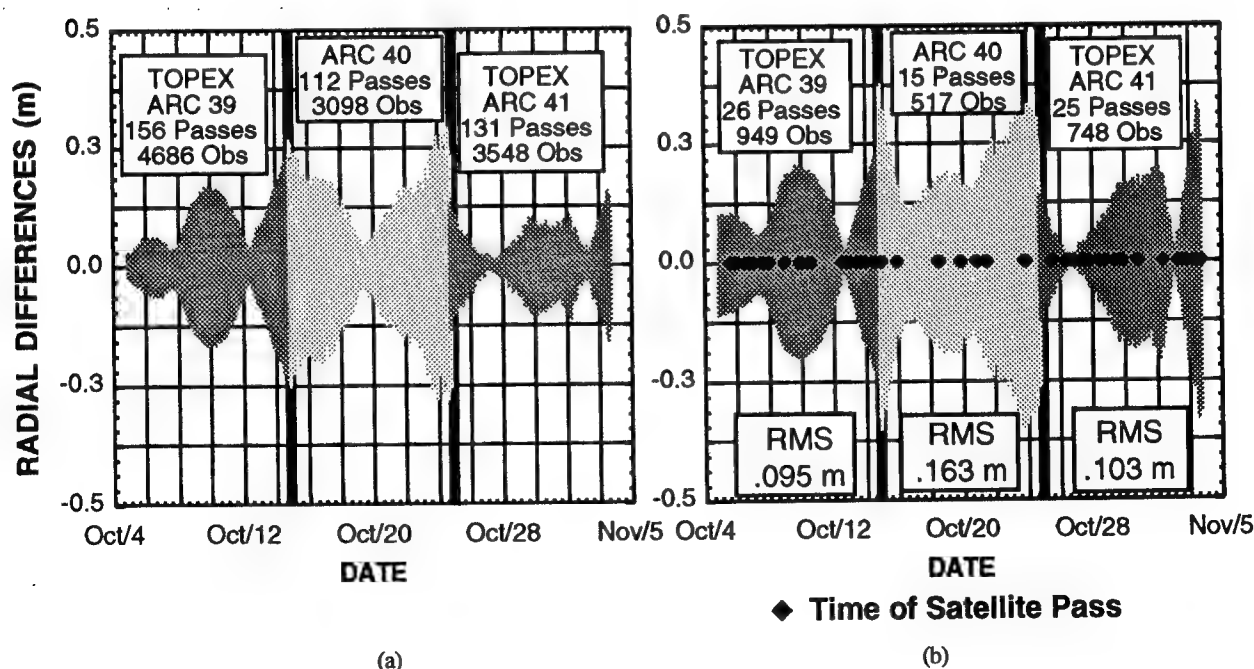


Fig. 9 — Radial position difference as compared to POE for three consecutive 10-day TOPEX cycles for (a) all SLR sites and (b) Monument Peak

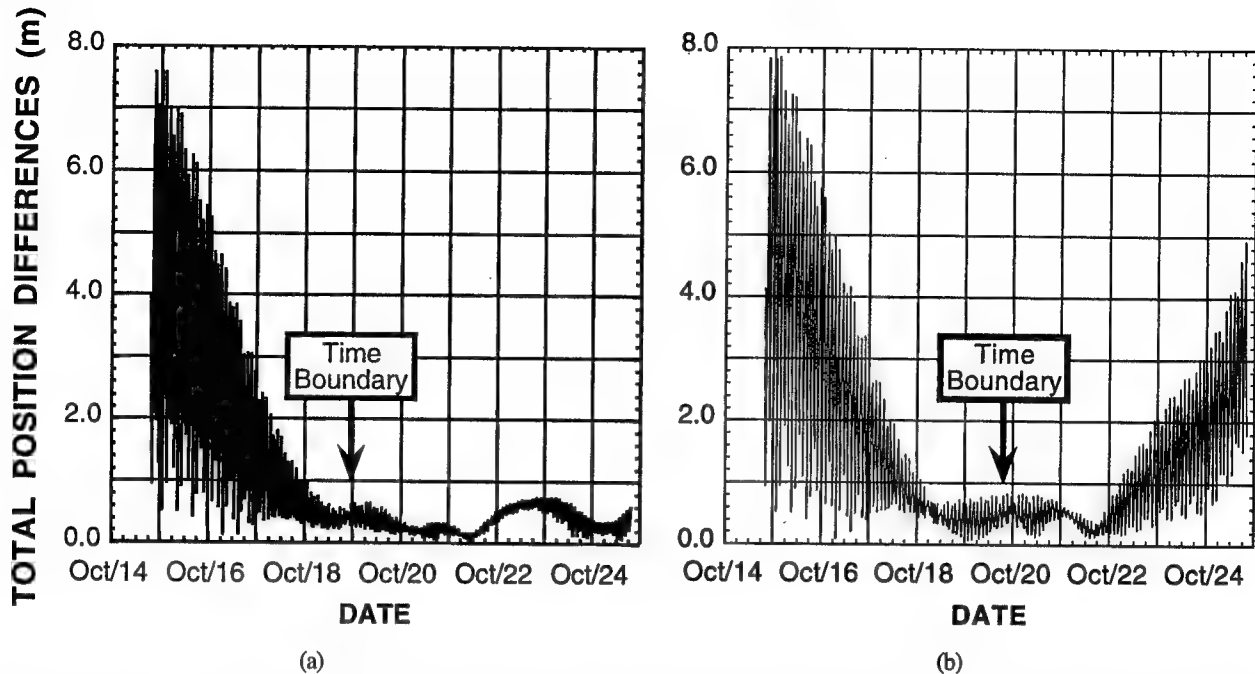


Fig. 10 — (a) Results of total position difference with the boundary for adjustments of the two D/R terms set halfway in time through the 10-day TOPEX Cycle 40. (b) The solution with the boundary of the D/R terms shifted to half the total number of observations.

In the first experiment, the time boundary was centered at half the total observations. The position difference increased in the beginning and end of the cycle. There was no overall reduction in residuals. Figure 10(b) shows these results. In the second experiment, one D/R value was solved for over all 10 days and compared to results using two consecutive D/R values. Figure 10(c) illustrates these results. Solving for a single D/R term over the whole 10-day cycle reduced the magnitude of the peak difference to 5.8 m.

In the final experiment, two passes were added to the beginning of the cycle. Figure 10(d) shows these results. Two consecutive D/R terms were solved for in this case with the boundary set at the midpoint of the total number of observations from 15 passes. The total position RMS difference was reduced to 0.68 m, with a peak value of 1.5 m. These results demonstrate the need for more observations at the beginning of the cycle to balance the data distribution and to meet the 15 pass criteria.

This series of computational experiments leads to two conclusions about manipulation of GEODYN to produce ephemerides. First, the results within a ground-repeat cycle can be changed significantly with very small changes to input conditions. Figure 10 illustrates the dramatic change in profile that can occur with changes in just one parameter.

This sensitivity to input variations leads to a second and critical conclusion. Specifically, the instantaneous position for a satellite can only be confidently known in terms of an RMS average. This average is determined over a repeat ground track after data and error reduction has occurred. The satellite position at a specific time in the cycle itself cannot be expressed more accurately than as the RMS difference from the POE because of the sensitivity of this uncertainty to input variation and to error-reducing strategies. Therefore, absolute position is expressed as an average value obtained over the ground repeat track for TOPEX using GEODYN in the cases studied.

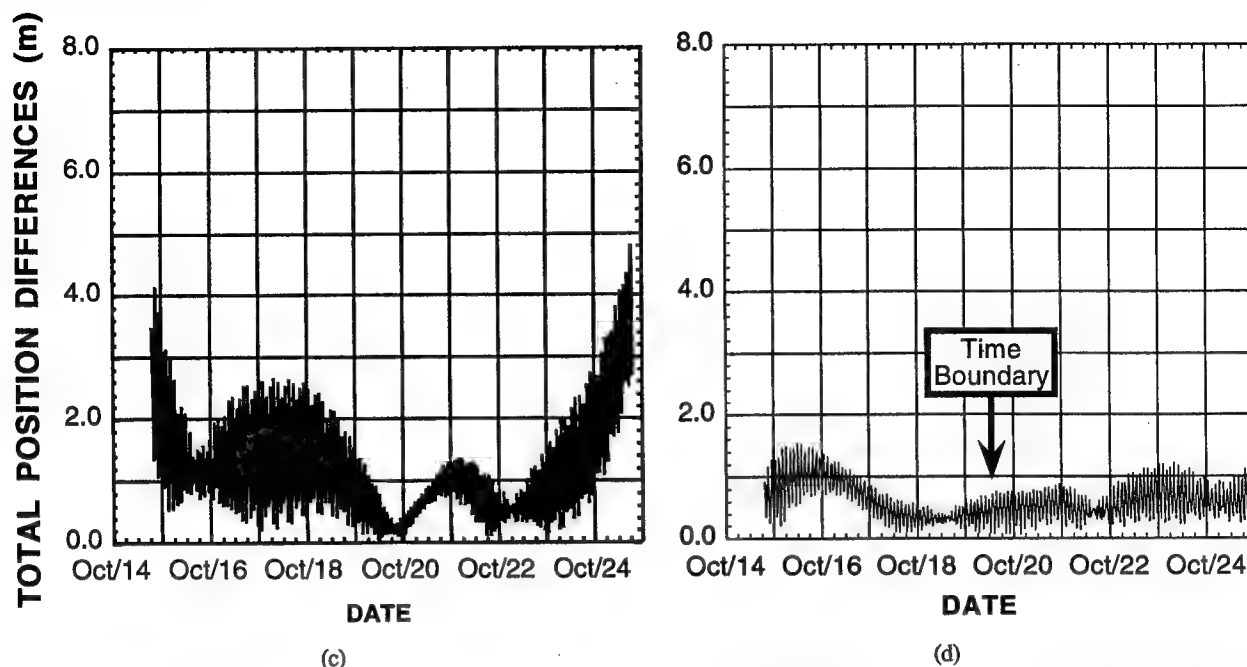


Fig. 10 — (c) Total position results using one D/R term over the 10-day TOPEX Cycle 40. (d) Demonstrated improvement in solution by adding two passes to the beginning of the 10-day cycle and setting the boundary of the two D/R terms by half the total observation.

4.3 Single-Site Shift Selection

An important implicit consideration throughout this analysis was the necessity for a good distribution of the observed passes. Previous simulations established the importance of minimizing revisit times for TOPEX. In this set of investigations, the need for good geometric distribution of the observed passes was established. For a single site, this need was met by tracking both the ascending and descending passes, each of which represents a different portion of the orbit. In this section, the ascending and descending passes were systematically removed to examine the implications in ephemeris accuracy. Since the site's opportunity to track these portions of the orbit is limited to certain times of the day, these results lead directly to an understanding of the importance of proper shift scheduling.

The high priority on tracking TOPEX largely dictated NASA shift schedules. If day and night shifts were run 7 days a week at the site, the site could observe all passes not obscured by weather. In fact, little of the data dropout considered in these cases can be attributed to shift scheduling.

Many of the sites, however, operated two 5-day shifts per week. Consequently, some of the available passes were missed. At NASA stations like Goddard, day and night shifts are typically staggered to reduce the duration of the longest coverage gap. Specifically, the night shift's week begins 2 days after the day shift's week. Weather permitting, this scheme fixed the maximum coverage gap to approximately 20 hours.

The potential absence of a second shift means that orbital sampling will be impacted and resulting ephemerides will be less accurate. The implications of single-shift staffing was investigated to determine the impact of missed passes on ephemerides obtained during postprocessing. Systematic removal of ascending or descending passes via removal of the day or night shift has a strong influence on the overall accuracy and is demonstrated in the following discussion.

The results presented in preceding sections show the impact of the coverage gaps. Ephemeris accuracy was better during Cycles 39 and 41 than during Cycle 40. Missed days were typically distributed throughout the 10-day interval and occurred somewhat randomly. More importantly, the day and night passes were equally likely to be missed.

In this part of the analysis, Monument Peak was selected as the single site. The impact of different tracking scenarios on ephemerides was determined. Table 2 summarizes these results.

Table 2 — Single-Site Ephemerides Differences for Monument Peak
with Different Tracking Scenarios

<u>Case</u>	<u>Shifts</u>	<u>Radial</u> (cm - RMS)	<u>Crosstrack</u> (cm - RMS)	<u>Alongtrack</u> (cm - RMS)	<u>Total Position</u> (cm - RMS)
1	All Passes	9	22	27	36
2	13 Passes	17	22	62	68
3	Day Only	101	75	389	409
4	Night Only	349	64	1282	1330

As can be seen from the table, when all the observed passes from Cycle 39 were used to perform the orbit update, the total position difference of 36 cm RMS was achieved for the resulting ephemeris. If an even distribution of 13 of these 27 passes were used, a total position difference of 68 cm RMS was obtained. However, if only 13 day passes were available, i.e., no night shifts to perform the orbit update, the total position difference with respect to the POE was 409 cm RMS. If only the 14 night passes were used, the total position ephemeris accuracy degraded to approximately 1,300 cm RMS.

The impact of missed passes on the final ephemerides produced in postprocessing is understood in terms of orbital sampling with respect to its geometry. When GEODYN has data from sites with a wide geographic distribution, the orbit for TOPEX can be determined to within 15 centimeters. The orbit may be considered to be a circle/ellipse with one focus at the geocenter. Determination of that orbit corresponds with fixing the position of the circle by using a set of fixed points. If the fixed points constrain different segments of a circle, then the result will be that the circle has very little freedom to shift and is well-fixed in inertial space.

Figure 11 illustrates the coverage of the TOPEX orbit during ascending and descending passes from Monument Peak, Goddard, and Yarragadee. When GEODYN uses the SLR observations from a single site as in Case 1 of Table 2, orbital sampling is significantly degraded. In good weather, TOPEX is typically in view of a single site three to four times daily. These passes, however, always view the same two portions of the orbit arc.

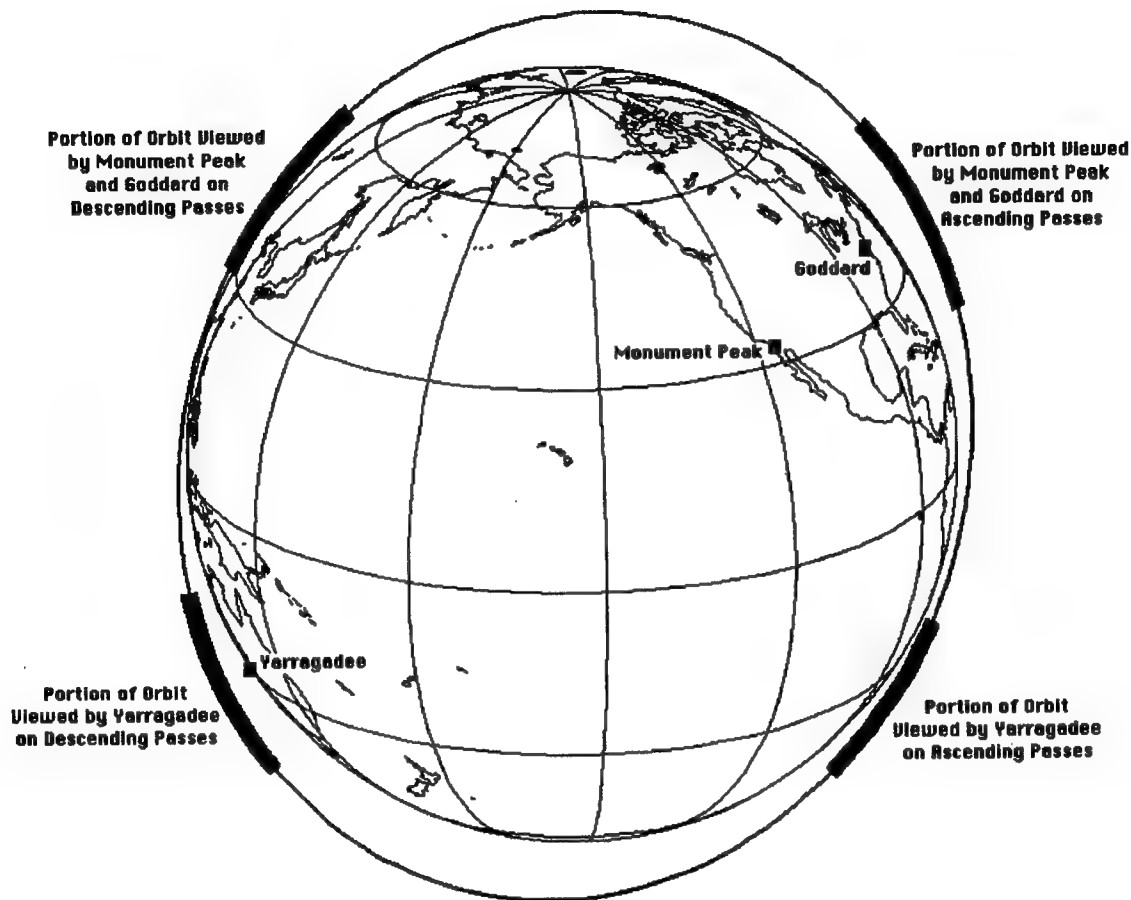


Fig. 11 — Illustration representing portions of TOPEX orbit trajectory as seen by Goddard, Monument Peak, and Yarragadee SLR sites

For a Continental United States (CONUS) site, TOPEX will be visible over a 20° arc of its orbit on either the ascending or descending portion of the orbit as seen in the figure. If the ascending passes occur during the day shift, then descending passes will occur over the site about 10 hours later during the night shift. When GEODYN updates the estimate of the orbit using this set of observations, it is effectively trying to determine the orbit by constraining the circle in two places instead of in several as available by orbital sampling from the entire network.

Consequently, in the case studied, instead of achieving accuracy at the few-centimeters level, the single site operating with day and night shifts attained accuracy at the tens-of-centimeters, 35 cm to 100 cm RMS level. Although the resulting solution still had sub- to one-meter accuracy, an order of magnitude degradation in the determination of the orbit resulted. This finding held true even when the number of dual-shift/single-site passes was evenly reduced from 27 to 13, as shown in Case 2 in Table 2.

The solution degraded by an order of magnitude when the observations were systematically reduced by removing either the day or night shift as shown in Cases 3 and 4 in Table 2. In these cases, TOPEX was tracked over only one portion of its orbit, instead of over two. Hence, GEODYN determined the ephemeris by constraining the orbit in only one location. The TOPEX orbit was basically unconstrained when the satellite was out of view. The consequence of omitting data from the corresponding ascending or descending passes was that the orbit ephemeris produced by GEODYN degraded to the multiple meter level, i.e., 4 m to 13 m.

4.4 Two Single-Shift SLR Sites

In the previous section, quantitative guidelines were established for the minimum data collection requirements from an individual site for submeter orbit determination. This section investigates orbital sampling using two SLR sites operating with single shifts. For a pair of cooperating sites, the pass distribution requirement can be met if each site tracks a different portion of the orbit.

For the case of two single-shift SLR sites tracking TOPEX, optimum shift coverage at those sites was determined. Table 3 presents a summary of the cases studied. Results are listed for each pairing of three sites: Goddard, Monument Peak, and Yarragadee. Corresponding ephemeris accuracy obtained for each pair during Cycle 39 is also listed. Table A1 gives the pass coverage for Monument Peak during Cycle 39. Tables A4 and A5 describe pass coverage for Goddard and Yarragadee for this cycle.

In the first case for each pairing, the ephemeris accuracy determined with all of the available passes is listed. These results are the most accurate, as is expected, due to optimum sampling of the orbit. Subsequent cases considered different combinations of day and night shifts.

The results for the pairing of Monument Peak and Goddard most clearly summarize the effects of the single-site, single-shift scenario. The day shifts at the two sites tracked the same approximate portion of the orbit, i.e., the portion of the ascending pass over the northern mid-latitudes. Similarly, the night shifts at these sites both tracked the part of the descending pass over the northern mid-latitudes.

These combinations are similar to the conditions under which single-site, single-shift orbit determination was studied. Twice as many observations, however, were available to update the orbit. In addition, the sites were located at slightly different latitudes and, therefore, do not track the exact same portion of the orbit. These two facts suggest that better accuracy might be obtained with the two sites operating at the same time of day than the single site such as is indicated with the day/day and night/night scenarios for Monument Peak and Goddard.

Another scenario summarized in Table 3 for the two CONUS sites consists of one daytime tracking site and one nighttime tracking site. In this case, each site observed different portions of the orbit and was effectively equivalent to a dual-shift single site. In both cases, the ephemeris difference was comparable to that computed from obtaining data from ascending and descending passes over the better of the two sites.

Table 3 — Two-Site Shift Scenario: Results

<u>Site 1</u>	<u>Site 2</u>	<u>Radial</u> (cm -RMS)	<u>Crosstrack</u> (cm -RMS)	<u>Alongtrack</u> (cm -RMS)	<u>Ttl Position</u> (cm -RMS)
Monument Peak	Goddard				
All	All	9	22	27	36
Day	Day	12	70	55	90
Day	Night	8	20	35	41
Night	Day	13	21	46	52
Night	Night	194	42	714	741
Monument Peak	Yarragadee				
All	All	8	22	24	34
Day	Day	8	60	35	70
Day	Night	12	21	37	44
Night	Day	9	20	37	43
Night	Night	17	20	63	68
Goddard	Yarragadee				
All	All	9	23	25	35
Day	Day	11	52	48	72
Day	Night	65	25	248	258
Night	Day	9	21	36	43
Night	Night	35	25	129	136

An additional scenario was studied to determine the impact of a combination of a CONUS site operating at one shift with an Australian node operating at its complement. GEODYN was provided with coverage from two different parts of the orbit. All of the shift combinations for Monument Peak and Yarragadee show that the ephemeris obtained by taking the single-shift observations from two high-quality, geographically displaced sites produced submeter position differences from the POE.

The final set of results in Table 3 summarizes the combination of single-shift passes over Goddard and Yarragadee. The day/day and night/day combinations give accuracy at the 72 cm and 43 cm RMS levels, respectively. These submeter results are nearly equivalent to dual-shift, single-site performance.

Two results presented in the last section of Table 3 were dependent more on data dropouts than on orbital geometry. The day/night and night/night combinations resulted in degraded ephemerides of 2.58 meters and 1.36 meters, respectively. The main reason for the loss in precision can be traced to data density and distribution. The data for Yarragadee shows that the site obtained data in only nine night-shift passes during Cycle 39. Yarragadee obtained no night-shift passes over the first 4 days of this cycle or over the last 2 days. Goddard had sparse data during these periods as well; i.e., 7-day and 7-night passes. Therefore, the site was unable to contribute many passes to the orbit updating process. As a result, the beginning and ending portions of Cycle 39 were essentially unconstrained. In contrast, the day shift at Yarragadee obtained data from 11 passes that were fairly well-distributed over the 10 days of the cycle. As such, the data from Yarragadee was able to constrain the orbit well enough to produce a better solution.

4.5 Multiple-Site Analysis

In this section, ephemerides differences using one or more sites were compared. The observations from additional sites were added incrementally to those of the initial single site to examine the improvement in the ephemeris solution. Cases through ten sites were compared. The drag and solar radiation terms were estimated for all cases and no AA parameters were adjusted. The initial site chosen in this case was an average site from the global SLR network. Typically, such a site had fewer than 15 satellite passes over the 10-day cycle, which was less than the number of passes deemed necessary for submeter accuracy.

The total position RMS difference vs an increased number of sites is shown in Fig. 12. The typical site, in this case Goddard, when considered as the only source of orbit sampling, estimated the position of TOPEX to approximately 26 cm cross track, 30 cm radial, and 100 cm along track. The total position RMS for these estimates was approximately 105 cm.

Significant reduction in the RMS ephemeris difference was observed after adding the observations from a judiciously selected second site, in this case Yarragadee. The RMS ephemerides difference was improved from 105 cm to 35 cm. As discussed in Section 4.4, these data were obtained from a noncoincident portion of the orbit.

Additional results not shown in the figure demonstrated that, in most cases, two SLR sites were sufficient for 43 cm RMS total position accuracy. Further, they showed that if a given single site had fewer than 15 passes, the addition of noncoincident passes from a second site reduced total position differences to less than 50 cm. The only qualification to this last statement was that these additional passes from a second site should cover a portion of the TOPEX orbit that had not previously been tracked.

It is important to note that with GEODYN, no significant improvement resulted from using the observations from more than two sites given this empirical orbit parameterization. This apparent limitation in GEODYN is related to how and when the anomalistic accelerations may be used to reduce the range residuals. Solving for AA was an underdetermined problem for a reduced number of sites. There may be some modifications that can be made to the program but that are beyond the scope of this study.

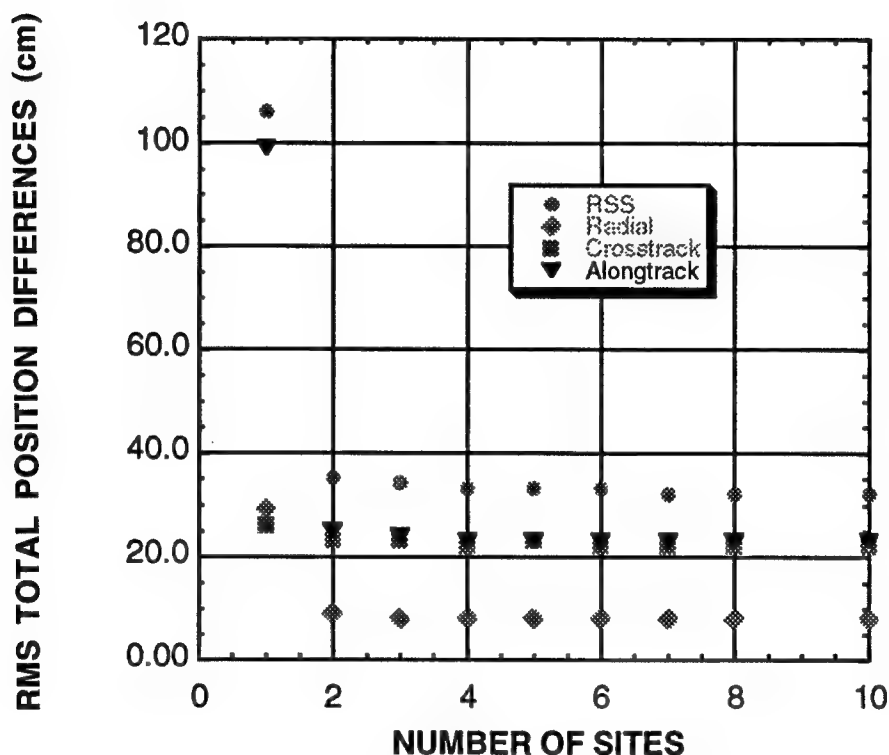


Fig. 12 — Total position difference vs an increased number of sites demonstrates that two SLR sites, which are noncoincident during measurements, provide 40 cm accuracy

5. SUMMARY OF RESULTS

This study showed that ephemerides can be determined in the submeter range for a reduced number of SLR sites by using a well-specified satellite. Initial conditions were self-generated and used to obtain submeter-level ephemeris for consecutive cycles. Shift coverage was shown to impact the solution significantly. Table 4 summarizes the cases and results from this study. All results were represented as position differences in ephemeris with respect to the POE. The total RMS position error of the POE was 15 cm.

The ability to achieve these levels of accuracy was demonstrated using specific sites that were constrained by stringent requirements on data acquisition and postprocessing conditions. Specifically, to obtain submeter ephemerides, at least 15 passes must be obtained, with a relatively even distribution of ascending and descending satellite passes with a maximum revisit time of less than 2 days throughout the solution interval. The model of the spacecraft used by GEODYN must be

very well defined and the force models complete to the level equivalent to that of TOPEX. In postprocessing, drag and solar radiation parameters were used to reduce RMS residuals, but AAs were not computed.

Results from the multiple-site analysis demonstrated that, in most cases, two SLR sites were sufficient for 43 cm RMS difference with respect to the POE. Further, they showed that if a given single site had fewer than 15 passes, the addition of noncoincident passes from a second site reduced total position differences to less than 50 cm. As in the single-site cases, solving for AA was found to be an under-determined problem using a reduced number of sites, i.e., fewer than ten. Hence, only drag and solar radiation pressure could be used to reduce the range residuals. It should be pointed out that although it is possible to obtain submeter ephemerides with a single site, this study indicates that it is much easier to do so with two judiciously selected SLR stations.

Table 4 — Summary of Results

Case	AA	D/R	Comments	Total Position RMS (cm)
All Sites	Fixed	Fixed (1)	NASA's A Priori Values	15
All Sites	None	Fixed (1)	Used to Compare with ->	123
All Sites	None	Adjusted (2)	Single/Multiple Site Cases	38
Single Site	Adjusted	Fixed	Could Not Converge	
Single Site	None	Fixed (1)	Best Single Sites	125
Single Site	None	Adjusted (2)	Best Single Sites	39
Single Site	None	Adjusted (2)	3 Consecutive Cycles	42/68/33
Single Site	None	Adjusted (2)	Average Single Sites	100 to 200
Two Sites	None	Adjusted (2)	2 Average Sites	43
Three Sites	None	Adjusted (2)	Reached Boundary	42
Nine Sites	None	Adjusted (2)	"	42

6. CONCLUSION

The results from this study were TOPEX/POSEIDON-specific. Submeter ephemerides were produced using optimum single SLR sites. The distribution and density of observations and passes had a significant effect on the ephemeris solution. The study demonstrated the ability to estimate satellite position using a single SLR site by optimizing the solution interval. Orbit differences, as compared with the POE, were reduced to less than 40 cm RMS total position for good SLR sites. Adding a second SLR site significantly relaxed requirements on a given first site. That is, ephemeris differences can be substantially reduced, from 100 cm to 40 cm RMS, when the single site collects data from a non-optimum number of passes or from a nonuniform distribution of passes caused by weather or system outages.

It is important to note that GEODYN cannot determine absolute position with respect to time beyond that of a total position average over a specific orbit arc. Results indicate a high sensitivity to

input variables, hence peaks and nulls in the data can be shifted arbitrarily, depending on data reduction strategies. Therefore, absolute position is expressed as an average. These results have implications for the use of GEODYN, or an equivalent batch least squares fit approach, in determining position of satellites for calibration of absolute position to the submeter level.

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Appendix

SUMMARY OF OBSERVATIONS FOR TOPEX CYCLES STUDIED: MONUMENT PEAK, GODDARD, AND YARRAGADEE SLR STATIONS

Table A1 — Monument Peak Observations for Cycle 39
(27 Passes: 13 Day/14 Night)

<u>Site #7110 (Monument Peak)</u>						
<u>Pass Start</u>	<u>Pass End</u>	<u>High Elev</u>	<u>Consec Passes</u>	<u>Max Elev (deg)</u>	<u>Obs</u>	<u>Day/ Night</u>
10/04/93 23:47	10/04/93 23:59	-	-	-	-	N
10/05/93 01:45	10/05/93 01:52	-	-	-	-	N
10/05/93 14:14	10/05/93 14:26	X	X	69	43	D
10/05/93 16:14	10/05/93 16:19		X	22	21	D
10/06/93 00:11	10/06/93 00:22	X		66	37	N
10/06/93 12:46	10/06/93 12:49		X	21	13	D
10/06/93 14:37	10/06/93 14:49	X	X	68	48	D
10/06/93 22:40	10/06/93 22:47		X	30	28	N
10/07/93 00:35	10/07/93 00:44		X	54	39	N
10/07/93 13:06	10/07/93 13:15		X	37	37	D
10/07/93 15:00	10/07/93 15:10		X	42	41	D
10/07/93 23:00	10/07/93 23:11		X	48	44	N
10/08/93 00:58	10/08/93 01:05		X	31	31	N
10/08/93 13:28	10/08/93 13:40	-	-	-	-	D
10/08/93 15:12	10/08/93 15:27	-	-	-	-	D
10/08/93 23:23	10/08/93 23:34	X		77	42	N
10/09/93 13:43	10/09/93 13:55	-	-	-	-	D
10/09/93 21:52	10/09/93 21:58		X	26	22	N
10/09/93 23:46	10/09/93 23:57	X	X	65	45	N
10/10/93 12:18	10/10/93 12:26		X	31	34	D
10/10/93 14:13	10/10/93 14:22		X	49	38	D
10/10/93 22:15	10/10/93 22:26	-	-	-	-	N
10/11/93 00:11	10/11/93 00:21	-	-	-	-	N
10/11/93 12:42	10/11/93 12:53	-	-	-	-	D
10/11/93 14:40	10/11/93 14:48	-	-	-	-	D
10/11/93 22:38	10/11/93 22:50	-	-	-	-	N
10/12/93 00:38	10/12/93 00:40	-	-	-	-	N
10/12/93 13:01	10/12/93 13:13	X		83	49	D
10/12/93 21:04	10/12/93 21:08		X	22	17	N
10/12/93 22:57	10/12/93 23:09	X	X	76	46	N
10/13/93 11:31	10/13/93 11:37		X	25	27	D
10/13/93 13:24	10/13/93 13:35		X	58	47	D
10/13/93 21:24	10/13/93 21:34		X	35	35	N
10/13/93 23:20	10/13/93 23:31		X	45	43	N
10/14/93 11:52	10/14/93 12:02		X	44	40	D
10/14/93 13:48	10/14/93 13:57		X	36	39	D
10/14/93 21:47	10/14/93 21:58		X	56	43	N
10/14/93 23:44	10/14/93 23:51		X	25	15	N

Table A2 — Monument Peak Observations for Cycle 40
(13 Passes: 4 Day/9 Night)

<u>Site #7110 (Monument Peak)</u>						
<u>Pass Start</u>	<u>Pass End</u>	<u>High Elev</u>	<u>Consec Passes</u>	<u>Max Elev (deg)</u>	<u>Obs</u>	<u>Day/Night</u>
10/14/93 21:47	10/14/93 21:58		X	56	43	N
10/14/93 23:44	10/14/93 23:51		X	25	15	N
10/15/93 12:18	10/15/93 12:30	-	-	-	-	D
10/15/93 14:19	10/15/93 14:23	-	-	-	-	D
10/15/93 20:22	10/15/93 20:25	-	-	-	-	N
10/15/93 22:11	10/15/93 22:21	X		87	38	N
10/16/93 10:49	10/16/93 10:55	-	-	-	-	D
10/16/93 12:41	10/16/93 12:53	-	-	-	-	D
10/16/93 20:43	10/16/93 20:52	-	-	-	-	N
10/16/93 22:38	10/16/93 22:49	-	-	-	-	N
10/17/93 11:10	10/17/93 11:20	-	-	-	-	D
10/17/93 13:06	10/17/93 13:16	-	-	-	-	D
10/17/93 21:05	10/17/93 21:17	-	-	-	-	N
10/17/93 23:03	10/17/93 23:10	-	-	-	-	N
10/18/93 11:26	10/18/93 11:37	X	X	64	43	D
10/18/93 13:24	10/18/93 13:31		X	26	29	D
10/18/93 21:28	10/18/93 21:40	-	-	-	-	N
10/19/93 11:55	10/19/93 12:07	-	-	-	-	D
10/19/93 19:49	10/19/93 19:55		X	26	25	N
10/19/93 21:43	10/19/93 21:55	X	X	65	48	N
10/20/93 10:24	10/20/93 10:33	-	-	-	-	D
10/20/93 12:19	10/20/93 12:30	-	-	-	-	D
10/20/93 20:11	10/20/93 20:21		X	41	40	N
10/20/93 22:07	10/20/93 22:17		X	38	26	N
10/21/93 10:37	10/21/93 10:48		X	53	45	D
10/21/93 12:37	10/21/93 12:43		X	30	26	D
10/21/93 20:42	10/21/93 20:54	-	-	-	-	N
10/22/93 11:09	10/22/93 11:21	-	-	-	-	D
10/22/93 19:11	10/22/93 19:18	-	-	-	-	N
10/22/93 21:05	10/22/93 21:17	-	-	-	-	N
10/23/93 09:38	10/23/93 09:47	-	-	-	-	D
10/23/93 11:32	10/23/93 11:44	-	-	-	-	D
10/23/93 19:23	10/23/93 19:32		X	35	38	N
10/23/93 21:19	10/23/93 21:24		X	45	22	N
10/24/93 10:00	10/24/93 10:11	-	-	-	-	D
10/24/93 11:57	10/24/93 12:06	-	-	-	-	D
10/24/93 19:55	10/24/93 20:07	-	-	-	-	N
10/24/93 21:55	10/24/93 21:59	-	-	-	-	N

Table A3 — Monument Peak Observations for Cycle 41
(23 Passes: 13 Day/10 Night)

<u>Site #7110 (Monument Peak)</u>						
<u>Pass Start</u>	<u>Pass End</u>	<u>High Elev</u>	<u>Consec Passes</u>	<u>Max Elev (deg)</u>	<u>Obs</u>	<u>Day/ Night</u>
10/24/93 19:55	10/24/93 20:07	-	-	-	-	N
10/24/93 21:55	10/24/93 21:59	-	-	-	-	N
10/25/93 10:13	10/25/93 10:23	X	X	70	31	D
10/25/93 12:13	10/25/93 12:16		X	22	16	D
10/25/93 20:19	10/25/93 20:31	-	-	-	-	N
10/26/93 08:45	10/26/93 08:46		X	21	7	D
10/26/93 10:36	10/26/93 10:46	X	X	68	29	D
10/26/93 18:37	10/26/93 18:44		X	30	26	N
10/26/93 20:32	10/26/93 20:37		X	54	21	N
10/27/93 09:03	10/27/93 09:12		X	37	38	D
10/27/93 10:58	10/27/93 11:08		X	42	39	D
10/27/93 18:58	10/27/93 19:08			48	43	N
10/27/93 21:07	10/27/93 21:14	-	-	-	-	N
10/28/93 09:24	10/28/93 09:35	X		63	46	D
10/28/93 11:36	10/28/93 11:41	-	-	-	-	D
10/28/93 19:22	10/28/93 19:31	X		78	36	N
10/29/93 08:08	10/29/93 08:12	-	-	-	-	D
10/29/93 09:46	10/29/93 09:56	X		75	36	D
10/29/93 18:01	10/29/93 18:09	-	-	-	-	N
10/29/93 19:48	10/29/93 19:54	X		65	12	N
10/30/93 08:28	10/30/93 08:38	-	-	-	-	D
10/30/93 10:23	10/30/93 10:34	-	-	-	-	D
10/30/93 18:10	10/30/93 18:20		X	41	39	N
10/30/93 20:06	10/30/93 20:15		X	38	37	N
10/31/93 08:50	10/31/93 09:02	-	-	-	-	D
10/31/93 10:49	10/31/93 10:56	-	-	-	-	D
10/31/93 18:46	10/31/93 18:58	-	-	-	-	N
11/01/93 09:07	11/01/93 09:10			42	13	D
11/01/93 17:15	11/01/93 17:22	-	-	-	-	N
11/01/93 19:09	11/01/93 19:21	-	-	-	-	N
11/02/93 07:29	11/02/93 07:34		X	25	24	D
11/02/93 09:21	11/02/93 09:32		X	58	41	D
11/02/93 17:23	11/02/93 17:31		X	35	33	N
11/02/93 19:18	11/02/93 19:27		X	45	37	N
11/03/93 07:48	11/03/93 07:59		X	44	42	D
11/03/93 09:46	11/03/93 09:54		X	36	33	D
11/03/93 17:44	11/03/93 17:53			56	37	N
11/03/93 20:00	11/03/93 20:01	-	-	-	-	N

Table A4 — Goddard Observations for Cycle 39
(15 Passes: 7 Day/8 Night)

<u>Site #7105 (Goddard)</u>						
<u>Pass Start</u>	<u>Pass End</u>	<u>High Elev</u>	<u>Consec Passes</u>	<u>Max Elev (deg)</u>	<u>Obs</u>	<u>Day/ Night</u>
10/04/93 20:24	10/04/93 20:31	-	-	-	-	N
10/04/93 21:56	10/04/93 22:05	X		64	36	N
10/05/93 10:56	10/05/93 11:01	-	-	-	-	D
10/05/93 12:26	10/05/93 12:35	X		74	37	D
10/05/93 20:24	10/05/93 20:31		X	47	31	N
10/05/93 22:20	10/05/93 22:26		X	39	25	N
10/06/93 10:55	10/06/93 11:01		X	38	24	D
10/06/93 12:50	10/06/93 12:57		X	48	31	D
10/06/93 20:46	10/06/93 20:55	X		72	37	N
10/07/93 11:21	10/07/93 11:25		X	56	14	D
10/07/93 13:15	10/07/93 13:18		X	32	16	D
10/07/93 21:08	10/07/93 21:17	X		75	37	N
10/08/93 10:12	10/08/93 10:15	-	-	-	-	D
10/08/93 12:05	10/08/93 12:13	-	-	-	-	D
10/08/93 20:02	10/08/93 20:10	-	-	-	-	N
10/09/93 10:33	10/09/93 10:41	-	-	-	-	D
10/09/93 12:30	10/09/93 12:36	-	-	-	-	D
10/09/93 20:25	10/09/93 20:34	-	-	-	-	N
10/10/93 10:56	10/10/93 11:05	-	-	-	-	D
10/10/93 18:54	10/10/93 19:00	-	-	-	-	N
10/10/93 20:21	10/10/93 20:29	X		86	35	N
10/11/93 11:20	10/11/93 11:28	-	-	-	-	D
10/11/93 18:49	10/11/93 18:53			36	19	N
10/11/93 21:15	10/11/93 21:18	-	-	-	-	N
10/12/93 09:48	10/12/93 09:56	-	-	-	-	D
10/12/93 11:45	10/12/93 11:51	-	-	-	-	D
10/12/93 19:40	10/12/93 19:49	-	-	-	-	N
10/13/93 09:41	10/13/93 09:48		X	45	29	D
10/13/93 11:37	10/13/93 11:44		X	42	27	D
10/13/93 20:04	10/13/93 20:12	-	-	-	-	N
10/14/93 10:34	10/14/93 10:43	-	-	-	-	D
10/14/93 17:38	10/14/93 17:46		X			N
10/14/93 19:00	10/14/93 19:12	X	X	84	42	N
10/15/93 08:02	10/15/93 08:13	-	-	-	-	D
10/15/93 09:59	10/15/93 10:08	-	-	-	-	D

Table A5 — Yarragadee Observations for Cycle 39
(18 Passes: 11 Day/7 Night)

<u>Site #7090 (Yarragadee)</u>						
<u>Pass Start</u>	<u>Pass End</u>	<u>High Elev</u>	<u>Consec Passes</u>	<u>Max Elev (deg)</u>	<u>Obs</u>	<u>Day/ Night</u>
10/04/93 19:30	10/04/93 19:37	-	-	-	-	N
10/04/93 21:24	10/04/93 21:36	-	-	-	-	N
10/05/93 09:33	10/05/93 09:39		X	24	24	D
10/05/93 11:26	10/05/93 11:37		X	56	47	D
10/05/93 19:52	10/05/93 20:03	-	-	-	-	N
10/05/93 21:49	10/05/93 21:58	-	-	-	-	N
10/06/93 09:53	10/06/93 10:04		X	43	43	D
10/06/93 11:50	10/06/93 11:59		X	34	38	D
10/06/93 20:15	10/06/93 20:27	-	-	-	-	N
10/07/93 10:16	10/07/93 10:27	X		74	43	D
10/07/93 18:46	10/07/93 18:50	-	-	-	-	N
10/07/93 20:39	10/07/93 20:51	-	-	-	-	N
10/08/93 09:09	10/08/93 09:19	-	-	-	-	D
10/08/93 10:38	10/08/93 10:49	X		67	47	D
10/08/93 18:43	10/08/93 18:47		X	22	17	N
10/08/93 20:36	10/08/93 20:48	X	X	69	49	N
10/09/93 09:32	10/09/93 09:43	-	-	-	-	D
10/09/93 11:31	10/09/93 11:37	-	-	-	-	D
10/09/93 19:04	10/09/93 19:13		X	36	37	N
10/09/93 20:59	10/09/93 21:09		X	40	41	N
10/10/93 09:27	10/10/93 09:39	X	X	62	48	D
10/10/93 11:26	10/10/93 11:32		X	24	26	D
10/10/93 19:54	10/10/93 20:06	-	-	-	-	N
10/11/93 08:25	10/11/93 08:33	-	-	-	-	D
10/11/93 09:51	10/11/93 10:01	X		76	37	D
10/11/93 18:23	10/11/93 18:32	-	-	-	-	N
10/11/93 20:18	10/11/93 20:29	-	-	-	-	N
10/12/93 08:21	10/12/93 08:27		X	29	25	D
10/12/93 10:13	10/12/93 10:24		X	47	39	D
10/12/93 18:16	10/12/93 18:24		X	30	35	N
10/12/93 20:12	10/12/93 20:22		X	48	41	N
10/13/93 09:10	10/13/93 09:22	-	-	-	-	D
10/13/93 19:08	10/13/93 19:21	-	-	-	-	N
10/14/93 07:41	10/14/93 07:48	-	-	-	-	D
10/14/93 09:34	10/14/93 09:45	-	-	-	-	D
10/14/93 17:38	10/14/93 17:46		X			N
10/14/93 19:00	10/14/93 19:12	X	X	84	42	N
10/15/93 08:02	10/15/93 08:13	-	-	-	-	D
10/15/93 09:59	10/15/93 10:08	-	-	-	-	D